ROSA: A CODE FOR FUEL MANAGEMENT

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Abstract

The main goal of fuel management is to reduce fuel cycle costs while complying with a range of constraints. This goal can be achieved by optimization of assembly composition and/or loading pattern design. At KEMA the ROSA code package has been developed for simultaneous fuel and core optimization. The code combines a reactor core simulator, a reloading pattern generator and optimization algorithms. The optimization is based on simulated annealing, a Monte Carlo algorithm which exploits the speedy reactor core simulator to the fullest. A large number of constraints and objectives, which may be highly complex, can be involved in the optimization.

Introduction

For light water reactors the problem of designing an optimal or nearly optimal reloading pattern, while complying with various constraints, is very complicated due to the enormous number of possible patterns as well as the non-linearity of the problem. Therefore an efficient optimization algorithm has to be used. In order to exploit the possibilities of such an algorithm the calculation of the core-physics has to be fast. At KEMA this has led to the development of ROSA (*Reloading Optimization by Simulated Annealing*), an optimization code package, which uses a simulated annealing algorithm for the optimization and a stripped and accelerated version of the reactor core simulator LWRSIM [1] to calculate the reactor physics behavior of the core.

Optimization

Usually the optimization of a reloading pattern is done for a given set of assemblies, while complying with a set of constraints. In ROSA it is also possible to vary the characteristics of a fresh fuel assembly, such as the (axial) enrichment and/or poison content, during the optimization process. In this way the reloading pattern as well as the fuel composition can be optimized simultaneously.

To a plant operator the quality of the optimization can be expressed by the following requirements:

1. The compliance to safety margins e.g.:
   - thermal limits ($F_{\Delta H}$ (or F_{xy}) , F_q)
   - temperature coefficient
   - shutdown margin
   - maximum burnup of assemblies/rods/pellets
   - rod power history
2. The economical potential of the pattern e.g.:
   - cycle length
   - discharge burnup
   - fuel cost
   - equilibrium cycle characteristics
3. Logistics e.g.:
   - limitation on characteristics of fuel assemblies available for control rod positions
   - limitation on the number of highly reactive fuel assemblies at the core periphery or at any other user defined region
   - compliance with symmetry requirements (octant, quadrant)

Simulated Annealing

The optimization used in ROSA is based on simulated annealing [2], a Monte Carlo optimization method that has proven itself in a wide range of fields (e.g. VLSI-chip design, travelling salesman problem etc.). This method is suited for problems where there are many local optima in a multi dimensional space.
In order to utilize simulated annealing we quantify the goodness of a reloading pattern with respect to the constraints and objectives. Let us call this quantity *E,* the internal energy of the system (in analogy with a thermodynamical system).
Presently ROSA considers the energy of the system to be a function of the following quantities:

- $F_{\Delta H}$ (the enthalpy rise hot channel factor)
- Cycle length
- F_q (the hot spot power peaking factor)
- Temperature coefficient (boron concentration)
- Discharge burnup
- Fuel cost
- Total cost (fuel cost + coast down energy loss)
- Assembly burnup maximum
- Rod burnup maximum
- Pellet burnup maximum

The simulated annealing process which is used is the following:
Given a reloading pattern C_i a new pattern C_{i+1} is generated by random permutation and/or rotation and/or composition change of some of the assemblies. The new pattern is accepted with the following criterion (the Metropolis criterion):

$$P[C_i \rightarrow C_{i+1}] = 1 \quad (\Delta E \leq 0)$$

$$P[C_i \rightarrow C_{i+1}] = e^{\frac{-\Delta E}{T}} \quad (\Delta E > 0)$$

At a certain value of the control parameter T, which we will call the temperature of the system, the probability that the system is in a particular state with energy E is given by the Boltzmann distribution $e^{-E/T}$ (in equilibrium).
Once equilibrium is reached, the temperature is reduced. Repeating this scheme will trap the system in a minimum energy condition. The quality of the solution obtained in this way depends mainly on the temperature reduction scheme and to a lesser extent on the initial value of T.

Furthermore, the set of possible reloading patterns is limited to the set defined by additional rules such as limitations on the number of MOX or poison-assemblies on control rod positions or restrictions on highly reactive fuel assemblies to be placed on the core periphery.

Neutronics Model

Since for getting good results with simulated annealing the number of patterns that needs to be considered is extremely large, a very fast reactor code is necessary. In ROSA a 3-dimensional coarse mesh reactor code (1x1x12 meshes per assembly) is used to calculate the power distribution and all other necessary quantities in a quarter core geometry. The code uses 2-group cross-sections, which can be calculated with the lattice code LWR-WIMS [3] at KEMA. However cross-section data from other codes can also be converted to the required ROSA format.
The neutronics model is based upon a kernel method. The influence of radial flux gradients inside the assemblies is accounted for by coupling with a 2-dimensional calculation, which uses 3x3 meshes per assembly. In case of MOX-fuel or poison rods a spectrum correction method can be used to model the vast spectral changes at assembly interfaces.
A number of time steps is evaluated for each promising loading pattern to calculate the cycle length accurately.

Results

Extremely high speeds of the code are obtained; CPU time can be as low as 5-10 ms for a quarter core on a HP735. This is achieved by using the very fast reactor core model and by intelligent early decision making with respect to feasibility of a pattern.
Good performance with respect to license code results is obtained for UO_2 as well as partial MOX-cores.
The normalized assembly power accuracy is 0.01-0.02. The $F_{\Delta H}$ peak accuracy is within 2-3% and the cycle length prediction is within a few days.

References

[1] Verhagen, F.C.M., Ontwikkeling en validatie van een fijnmazig kernmodel voor de kerncentrale in Borssele, KEMA 1988, report 60118-RS 88-4019.
[2] Kirkpatrick, S. et al., *Science* **220**, 671-680 (1983)
[3] Halsall, M.J., 1982, LWR-WIMS a computer code for light water reactor calculations, AEEW-R 1498.